ELECTRON COOLED BEAM LOSSES PHENOMENA IN COSY

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Abstract

Experimentally it has been shown the achievable intensity of electron cooled beams at COSY is restricted by three main beam loss phenomena: the initial losses just after injection during 5-10 s of beam cooling, the coherent self-excited oscillation of cooled beam and the long-term losses ~n x 1000 s. In this work we study the first and third types of loss and compare the theoretical and experimental results.

INTRODUCTION

The problem of the electron cooled beam losses in COSY leading to not clearly short lifetime of a beam was already repeatedly investigated [1]. For the first time one has sounded, that the electron beam can not only cool the ion beam, but also heat it up in paper [2], where this phenomena was named “electron heating”. Many authors suggest explaining it by the nonlinearity of an electron beam field but not specifying what it does mean [3], except [4] in which the assessment of nonlinear resonances influence due to an electron beam is made.

The COSY ring is operating for medium energy experiments in the energy range 45-2500 MeV. During regular operation of the ring for experiments, the time spend at injection energy is about 100 ms short enough, that in the past no optimization of beam lifetime was carried out. At higher energies the beam lifetime is significantly longer, and no special measures are needed. To investigate the situation for the planned spin filtering studies, the status of beam lifetime at injection energy was studied. Recently the careful study to understand the beam lifetime of the proton beam at COSY injection energy of 45 MeV was undertaken.

In given work the results can be divided on two parts: experimental on measurement of beam lifetime and the theoretical part which has been directed on creation of mathematical model and treatment of experimental results. Following chronology of results receiving we begin with an experimental part. In theoretical investigation we are based on the concept of the isolated resonances with bridge between them due to diffusion arising because of scattering on residual gas. Besides it is assisted also with the additional e-beam chromaticity induced by an electron beam itself. In addition very low relative displacement of e- and p-beams can play strengthening role in losses of p-beam since it leads to excitation of odd resonances and decreases the distance between adjacent separatrix.

PROBLEM STATEMENT

At carrying out of experiments we at once tried to allocate the possible reasons for beam losses: fast immediate loss of particles in a single collision and leaving of stable region (dynamic or physical aperture) and slow blow-up of a beam which is caused by multi-acts process. Against the slow blow-up of beam there was an argument that it can be compensated by suitable cooling systems whereas the immediate loss of particles can not. In other words the real reason for particle losses maybe one-act process resulting in the output of a particle from under influences of cooler. The processes which cause immediate loss of particles are: hadronic interaction, single Coulomb scattering, multiple scattering, recombination and energy loss. We have compared possible probability of each process and have concluded the dominant processes which determine the achievable beam lifetime are the single Coulomb and multiple scattering. In presence of a sufficient electron cooling in COSY the multiple scattering can also be neglected, as scattered particles will be cooled back to the core of the beam before the next collision takes place. However this process also is left among candidates as under certain conditions electronic cooling cannot compensate this process.

FIRST BEAM LIFETIME MEASUREMENTS AT COSY

The 184 m long COSY ring is divided into 8 sections. In each section one quadrupole mass spectrometer measurement was taken to determine the partial pressure distribution of the rest gas. This gas distribution was then scaled with the overall 40 total pressure gauge measurements to obtain a realistic distribution of partial pressures all around the ring. The contribution of the 9 most abundant gases was used together with the Twiss parameters from a MAD code of the ring to calculate the contributions to the beam lifetime $\tau=1/(\Delta\sigma_C d_t f_b)$ with the real target density d_t, the revolution frequency of the beam f_b and Coulomb loss cross section $\Delta\sigma_C$.

Measurements of the beam lifetime were carried through with and without a D_2 target of density 2 10^{14} atoms/cm^2. The time behaviour of the stored beam current measured by a beam current transformer (BCT) was fit with an exponential decay function to yield the beam lifetime. The measured beam lifetimes are τ(with target) = (321.3 ± 0.4)s and τ(without target) = (4639 ± 69)s, which is about a factor ~15 smaller than the calculated beam lifetime. More details can be found in [5,6].

The possible explanations of the discrepancy of measurement and prediction based on single Coulomb scattering losses are: overestimation of the local acceptance or/and insufficient beam cooling.

Two different methods to measure the acceptance of the COSY ring were used: measurements with a single turn angle kick of the beam using a fast kicker magnet and measurement of beam lifetime versus position of scrapers.

The measurements with a fast kicker magnet used to determine the geometric acceptance of the COSY ring yields approximately 40 μm (see Fig. 1).

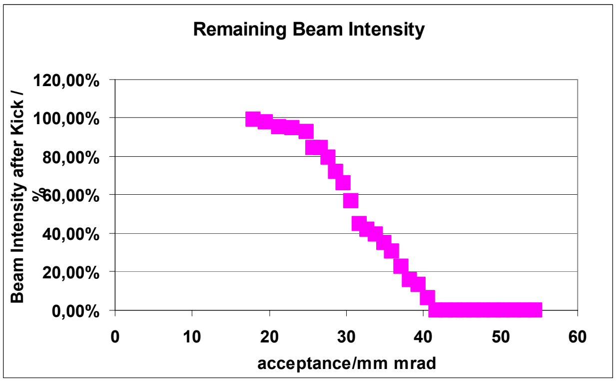


Figure 1: Acceptance measurement with fast kicker magnet. Fractional beam intensity versus acceptance, the acceptance is calculated from the used kick angle and the Twiss functions at the location of the kicker.

The second method [7] uses scrapers to restrict the acceptance of the ring (Fig. 2). Plotted results are the inverse of the beam lifetime τ^{-1} versus scraper position. The scraper consisted of a rectangular aperture, the beam passes through its centre. When the aperture is moved from the centre, no change in beam lifetime is observed until the edge of the aperture reaches the beam. When the scraper is moved more, the beam lifetime gradually goes to zero, and the distance determines the acceptance of the ring. To calculate the acceptance the Twiss functions at the scraper position are taken from a MAD.

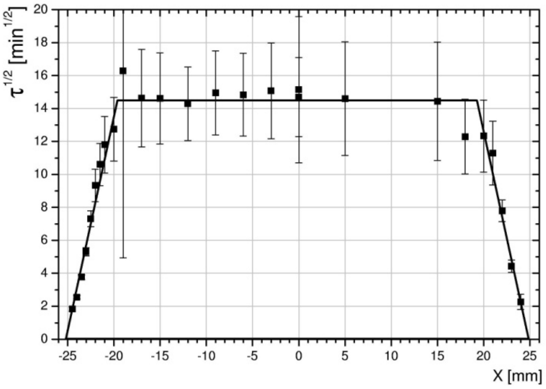


Figure 2: Acceptance measurement with scrapers.

The beam lifetime was determined from the exponential decay of the beam current measured with the BCT. During these measurements the circulating beam undergoes many revolutions in the ring. Therefore here also dynamic effects will be present. The measurements were done with uncooled and electron cooled beam. The results from these measurements agree well with the kicker measurements in the case without electron cooling. However, for electron cooled beam the measured acceptance has appeared 14 μm, which significantly less than value expected from estimation. We conclude from this, that the machine acceptance was overestimated in the beam lifetime calculation, and the actual machine acceptance for a cooled beam is significantly lower.

PHYSICAL AND DYNAMIC APERTURE WITHOUT ELECTRON BEAM

First of all we have calculated the dynamic aperture of COSY with the non-linearity caused by the optical channel only and without of electron beam. From the tracking we have found out the dynamic aperture value in all options is about of ~1000 μm, which one gives a hope to be sure that it is not reason for the lifetime decreasing. On a following step we have defined the physical aperture of the COSY channel with installed collimators. These sizes have appeared such value of 300 and 100 μm in the horizontal and vertical planes accordingly. Thus the dynamic and physical apertures without electron beam should be excluded from candidates of the particle losses source.

ELECTRON BEAM INFLUENCE ON DYNAMIC APERTURE

The electron beam used to cool the proton beam has two components of interaction: the particle-particle interaction and the particle-collective field interaction. The first one is the main component allowing the proton beam cooling and the second one is the effect acting on the proton beam as the multi-pole focusing/defocusing element. Here we investigate just second component. From the COSY e-cooler parameters we know that the electron beam has 175 mA and the uniform distribution in the transverse plane with the radius of cylinder of ±12.5 mm. In numerical calculation we consider two cases, when the electron beam has the uniform and Gaussian distributions with the current I_{el}, the radius r_{el}, the dispersion σ_{el} and the relative velocity β. For the e-beam with axial symmetry the radial force of electrical and magnetic fields of e-beam for the Gaussian distribution is:

$$F_{Gauss} = \frac{eI_{el}}{2\pi\varepsilon_0 c\beta\gamma^2} \cdot \frac{1}{r}\left(1 - \exp(-r^2/2\sigma_{el}^2)\right) \qquad (1)$$

and for the uniform distribution:

$$F_{unif} = \begin{cases} \dfrac{eI_{el}}{2\pi\varepsilon_0 c\beta\gamma^2 r_{el}^2} \cdot r, & \text{for } r < r_{el} \\ \dfrac{eI_{el}}{2\pi\varepsilon_0 c\beta\gamma^2 r} & \text{for } r > r_{el} \end{cases}, \qquad (2)$$

First we construct the N-order polynomial approximation of the e-beam force by the minimization of the mean-square deviation in some range $r<R_{max}<$Aperture of the space charge force averaging for the uniform and Gaussian distribution correspondingly [8]. Then it is approximated by the set of N=1÷10 multi-poles fields:

$$\mathrm{Min}_{r<R_{av}}\left\{\left[E_r(r) - b_1 \cdot r - b_3 \cdot r^3 - b_5 \cdot r^5 + \ldots\right]^2\right\} \qquad (3)$$

Within the frame of such approximation an electron beam is presented, as the periodic nonlinear short kick with a period of orbit circumference C_{orb} and at $L/C_{orb} \ll 1$:

$$F(r,\vartheta) = \left[b_1 \cdot r + b_3 \cdot r^3 + b_5 \cdot r^5 + \ldots\right] \cdot \frac{2L}{C_{orb}} \left[\frac{1}{2} + \sum_{p=1} \cos p\vartheta\right] \quad (4)$$

where all coefficients $b_n \propto I_{el} / (\beta\gamma^2 \sigma_{el}^2)$. Then using the asymptotic method of Bogolyubov-Mitropolsky [9] we seek a solution of equation in form $\frac{d^2 r}{d\vartheta^2} + K(\vartheta) r = 0$ after Courant-Snyder transformation in form $r = \sqrt{\bar{\varepsilon}\hat{\beta}} \cdot \cos(\nu_0 \vartheta + \bar{\Phi})$:

$$\begin{aligned} \frac{d\bar{\varepsilon}}{d\vartheta} &= \frac{1}{2\pi} \int_0^{2\pi} \sin\Phi \cdot F\left(\sqrt{\bar{\varepsilon}} \cos\Phi, \vartheta\right) d\Phi \\ \frac{d\bar{\Phi}}{d\vartheta} &= \frac{1}{2\pi\varepsilon^{1/2}} \int_0^{2\pi} \cos\Phi \cdot F\left(\sqrt{\bar{\varepsilon}} \cos\Phi, \vartheta\right) d\Phi \end{aligned} \quad (5)$$

Conditions of n-th order resonance are standard: $\nu(r) \cdot n = p$, where n-resonance order, p-arbitrary integer and $\nu(r) = \nu_0 + \frac{d\bar{\Phi}}{d\vartheta}$. The total tune shift $\frac{d\bar{\Phi}}{d\vartheta}$ is a sum of coherent and incoherent non-linear tune shifts:

$$\frac{d\bar{\Phi}}{d\vartheta} = \Delta\nu_{coh} + \delta\nu(r) . \quad (6)$$

The coherent tune shift and the non-linear tune shift of n-th order resonance are:

$$\Delta\nu_{coh} \sim \frac{I_{el}}{\beta\gamma^2 \sigma_{el}^2} \cdot \hat{\beta} \cdot L \quad (7)$$

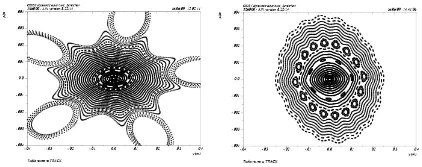
$$\delta\nu(r) \sim \frac{I_{el}}{\beta\gamma^2 \sigma_{el}^2} \cdot n \cdot \varepsilon^{n/2-1} \cdot \hat{\beta}^{n/2} \cdot L \quad (8)$$

At equality of a total e-beam current over cross section and equal dispersion the coefficients in the Gauss distribution about in 2 times are more than the uniform distribution. If beams are strictly on one axis at both distributions even resonances are raised only. In case of absence of a resonant condition nevertheless the electron beam brings nonlinear tune shift:

$$\delta\nu_{oct}(r) = \frac{d\bar{\Phi}}{d\vartheta} = \frac{3b_3 \cdot \nu_0 \cdot L\hat{\beta} \cdot r^2}{16\pi} , \quad (9)$$

and causes the displacement and smearing of a working point on the diagram of stability and excites all crossed resonances.

Walking in the stability diagram it is interesting to observe as phase trajectories change (see Fig. 3). Varying slightly tune ν_y value from 3.640 (a) to 3.613 (b) by the gradients in quadrupoles we cross different resonances modifying the phase trajectories.

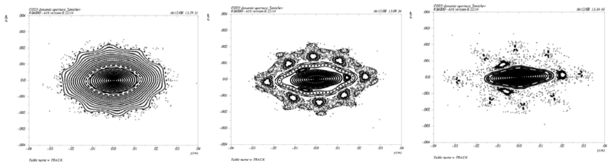


(a) (b)

Figure 3: Phase trajectory in vicinity of 10-th order resonance with tune ν_y =3.640 (a); 3.612648 (b).

Thus, the e-beam affects on the proton beam as the multi-pole field and together with magneto-optic elements can influence on the dynamic aperture. To investigate this problem the multi-pole element has been inserted in MAD file in the place of e-cooler location. The strength of each multi-pole component was determined by the mentioned above method.

First of all it was interesting to study, how the current value of e-beam influences character of single particle motion of a cooled beam. Figure 4 shows as the stable area changes versus e-beam current increased from 175 mA up to value in 7 times of higher.



(a) (b) (c)

Figure 4: Phase trajectories of cooled beam at uniform e-beam with σ_{el}= 6 mm and current: 175mA (a), 3 x 175 mA (b), 7 x 175 mA (c)

In the further we shall discuss a definition of the maximal stable area with e-beam, but at the moment we shall define it as the maximal phase area within the limits of area up to the nearest resonance. Then, proceeding from this definition we shall calculate the dependence of stable area on a current value (see Fig. 5). Apparently, with current increasing the stable area should shrink.

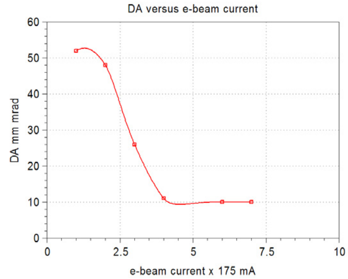
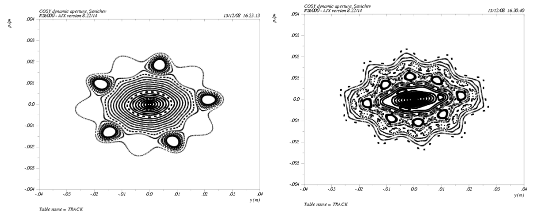


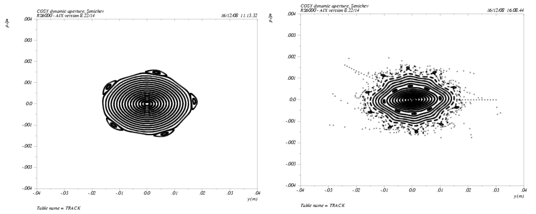
Figure 5: DA vs e-beam current (monochromatic p-beam and uniform e-beam).

Certainly also it is interesting to test on our model how at reduction of the electron beam sizes and constant value of a current the border of stability moves to the center (see Figs. 6 and 7).



(a) (b)

Figure 6: Phase trajectories for monochromatic p-beam cooled by the Gaussian e-beam with σ_{el}= 6 mm (a), 3 mm (b) and current 175mA.



(a) (b)

Figure 7: Phase trajectories for monochromatic p-beam cooled by the uniform e-beam with σ_{el}= 6 mm (a), 3 mm (b) and current 175mA.

Non-monochromatic Beam

In a reality the beam has final momentum spread, and at injection in COSY it is Δp/p~ 10-3. Therefore it is reasonable to consider what new instants appear for non-monochromatic beam. For this purpose let us write Hamiltonian with momentum spread and see its additional members arising owing to e-beam field:

$$\begin{aligned}
&H = H_0(p_x,p_y,\delta)+V(x,y,s)\\
&H_0(p_x,p_y,x,y,z)=\frac{p_x^2+p_y^2}{2(1+\delta)}+(K_x+\Delta K_x)\cdot\frac{x^2}{2}-(K_y+\Delta K_y)\cdot\frac{y^2}{2},\\
&V(x,y,s)=\frac{S_x(z)}{6}\cdot x^3+\frac{S_{xy}(z)}{2}\cdot xy^2+\frac{O_x(z)}{24}\cdot x^4+\frac{O_y}{24}\cdot y^4,\\
&K_x = K,\\
&\Delta K_x=\delta\cdot D\cdot S,\\
&K_y=-K,\\
&\Delta K_y=-\delta\cdot D\cdot S,\\
&S_x=S+\delta\cdot D\cdot O,\\
&S_{xy}=-S-\delta\cdot D\cdot O,\\
&O_x=O,\\
&O_y=O,\\
&K=\frac{1}{\beta c}\frac{\partial E_x}{\partial x};S=\frac{1}{\beta c}\frac{\partial^2 E_x}{\partial x^2};O=\frac{1}{\beta c}\frac{\partial^3 E_x}{\partial x^3}
\end{aligned}\tag{10}$$

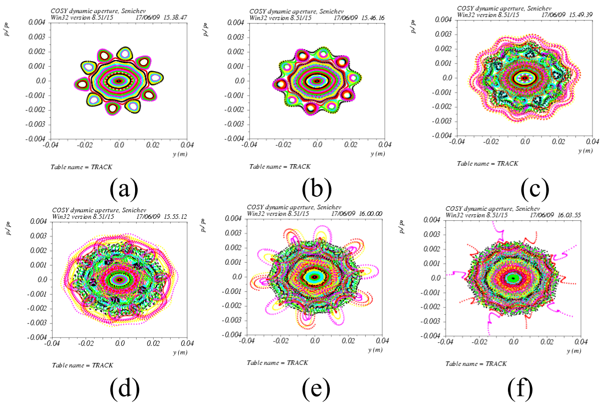
where K, S and O are multipoles of e-beam field. From Hamiltonian we can see that each multipole of n-th order gives all multipoles of 1÷ (n-1)-th order in the place where D≠0. In particular, the octupole component of e-beam generates sextupole. Therefore both even and odd resonances are raised. For COSY we have defined numerically the chromaticity without e-beam:

$$\varsigma_x=-8.5-400\cdot\left|\frac{\Delta p}{p}\right|;\varsigma_y=-0.2-1.0\cdot\left|\frac{\Delta p}{p}\right|$$

and with e-beam:

$$\varsigma_x=-9.1-7300\cdot\left|\frac{\Delta p}{p}\right|;\varsigma_y=-0.8-12000\cdot\left|\frac{\Delta p}{p}\right|.$$

We can see that e-beam induces the huge chromaticity, and we should expect a change of particles phase trajectories of cooled beam. Besides, chromaticity leads to emittance growth $\Delta\varepsilon/\varepsilon=0.5\cdot\varsigma^2\overline{(\Delta p/p)^2}$ due to smearing of trajectories.



(a) (b) (c)

(d) (e) (f)

Figure 8: Phase trajectories of non-monochromatic p-beam with Δp/p=0.0 (a); $\pm1\cdot10^{-4}$(b); $\pm3\cdot10^{-4}$(c);$\pm5\cdot10^{-4}$(d); $\pm8\cdot10^{-4}$(e); $\pm1\cdot10^{-3}$(f) cooled by the Gaussian e-beam with σ_{el}= 6 mm and current 175mA .

In order a process of particle smearing was visible we have marked particles in different layers with different color (see Fig. 8), and we can see that the process of chromatic smearing leads to the diffusion of particles from the centre. It is observed during several thousand turns by tracking (in real machine it is few seconds), and coincides with that we saw in experiment directly after injection of a beam in COSY at beginning of cooling.

Thus, at an initial stage of cooling the particle with a larger momentum deviation have to be lost, that most likely we also see in experiment and call as "fast losses"[10]. Figure 9 shows the stable area versus a momentum spread.

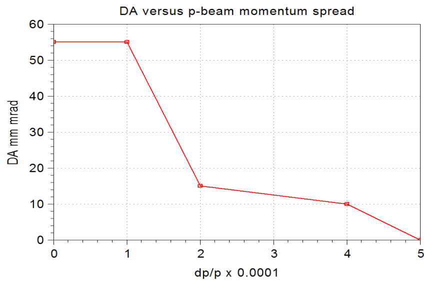


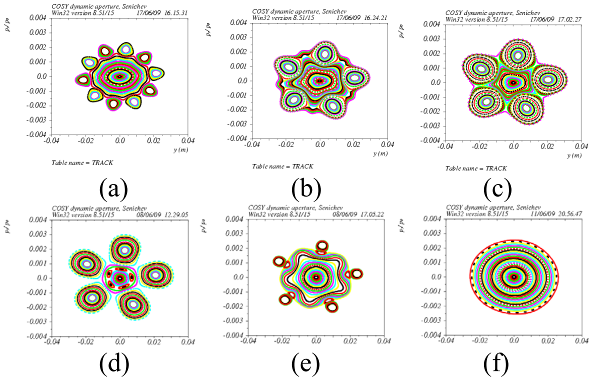
Figure 9: Stable area vs momentum spread.

Optics with Misalignments of p,e-Beams

In one of experiments [11] the e-beam was displaced relatively of a cooled beam and p-beam loss immediately grew. For comparison with results of experiment we have done the same on model. Apparently, that at e-beam displacement from axis $x_{co}=\Delta x+x$, $y_{co}=y+\Delta y$ the n-th order multipole of e-beam field gives all multipoles of 1÷(n-1)-th order. In particular, for a octupole component it is:

$$\frac{b_3}{4}\left(x_{co}^4 + y_{co}^4\right) = \frac{b_3}{4}(x^4 + y^4 4x^3\Delta x + ... + y^4 + 4y^3\Delta y + ..) \quad (11)$$

As a result odd resonances will be raised at zero dispersion in the cooler location too. Here we do accent on odd resonances excitation, since process of diffusion of particles is proportional to density of resonances. We modelled displacement of e-beam relatively of a proton beam. Figure 10 shows how in process of p-beam egress from e-beam field the even resonances disappear, and they are replaced by stronger odd resonances quickly reducing a stable area. However after beams fully splitting the phase trajectories take a form of linear oscillator. Figure 11 shows this process in numerical expression. It is visible, that at displacement of e-beam precisely on edge p-beam (shift=12 mm) the stable area decreases at the most.


(a) (b) (c)

(d) (e) (f)

Figure 10: Phase trajectories vs e-beam shift: 0mm (a), 4 (b), 8 (c), 12 (d), 25 (e), 40 (f).

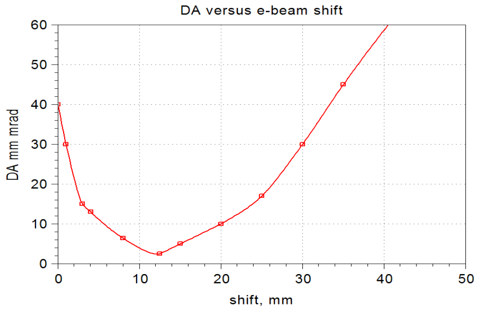


Figure 11: Stable area vs e-beam shift.

LOSSES MECHANIZM DISCUSSION AND CONCLUSION

Thus the physical model of e-cooled beam losses includes the following: particles circulating on an orbit and colliding with molecules of residual gas somewhere outside of cooler deviate from axis and are grasped in one of nonlinear resonances. To jump in the next resonance deflecting a particle further away from axis some factor is necessary. In a basis of our concept the following lays: missing link in model of the isolated resonances is the migration of particles from one resonance in another either due to accidental impact of a particle with molecules of residual gas, or smearing of phase trajectories due to the induced e-beam chromaticity or both ones. The displacement of one beam relatively another is additional strengthening effect. In Fig. 12 two cases for shifted e- beam and monochromatic and non-monochromatic p-beam are shown for comparison.

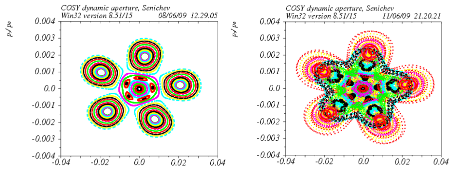

(a) (b)

Figure12: Phase trajectories for monochromatic (a) and non-monochromatic (b) beam.

In the first case a continuous deviation of a single particle is probable only at scattering on residual gas. In the second case it is provided by induced e-beam chromaticity.

Passing to the technical parameters of the accelerator the major factors leading to reduction of stable area and consequently to reduction of a cooled beam lifetime are: the values of dispersion and β-functions in a cooler, the relative displacement of beams and the uncorrected chromaticity induced by e-beam.

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